

**FINAL TECHNICAL REPORT  
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Origins of Solar Systems**

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**"Dynamical Evolution of Planetary Embryos"**

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During the past decade, progress has been made by relating the "standard model" for the formation of planetary systems to computational and observational advances. A significant contribution to this has been provided by this grant. The consequence of this is that the rigor of the physical modeling has improved considerably. This has identified discrepancies between the predictions of the standard model and recent observations of extrasolar planets. In some cases, the discrepancies can be resolved by recognition of the stochastic nature of the planetary formation process, leading to variations in the final state of a planetary system. In other cases, it seems more likely that there are major deficiencies in the standard model, requiring our identifying variations to the model that are not so strongly constrained to our Solar System.

One such serious situation is a consequence of observational discovery of more than 100 extra solar planets, mostly by our departmental colleague Paul Butler and his colleagues here and in other institutions. At present, except for bodies quite close to their "Sun," these objects are somewhat larger than our largest planet, Jupiter, but this is almost certainly simply a practical outcome of the present difficulty of detecting smaller bodies at large distances from their central star. A very important thing, contrary to the prediction of the standard model, is that in the course of their growth most gas giant planets seem to have drifted rapidly into their "Sun." This does not appear to have happened in any great extent in our Solar System. This may simply have been the consequence of the fact that planetary systems with a Jupiter where Earth should be are simply not likely to have planets sufficiently similar to Earth to evolve organisms comparable to humans in their ability to support astronomers. As a result, it seems likely that the standard model should be replaced with a more general theory of planet formation that incorporates both the most commonly observed systems, as well as those occasionally similar to our Solar System.

This is obviously a project too difficult to be carried out anywhere near to its completion, in a few years and by a few people. We thought it worthwhile, however, to consider that

our Jupiter and Saturn are likely to be an expected, but somewhat unusual, statistical case, and the observed giant planets with their rapid inward drift may be the conventional situation. If so, the formation of our giant planets must be quick, in order to allow Jupiter and Saturn to grow to their final sizes before they drift too far. This is in agreement with the "nonstandard" model developed extensively by my departmental colleague Alan Boss, in which Jupiter and Saturn form rapidly ( $< \sim 1$  million years) by gravitational instabilities during a late stage of the formation of the Sun. An extension of this nonstandard "core accretion" model, to include the ice giant planets Uranus and Neptune, has been published by Boss and Wetherill.

The first step in our program was to establish the dynamic processes that determine the growth with time of an assemblage of planetesimals in which the primary gravitational perturbations are those of the early-formed giant planets, rather than the mutual perturbations of the planetesimals with one another. The consequence of this is that on the average the relative velocities of the planetesimals with respect to the plane of the preplanetary disk are much greater than in the standard model, in which Jupiter and Saturn are not formed until the growth of terrestrial planets has reached sizes as large as those of the present planet Mars.

Our postdoctoral fellows, S. Kortenkamp and Satoshi Inaba, together with the PI, were able to show that formation of the terrestrial planets could still take place, despite these high velocities that one might guess would preclude such growth as a result of the destruction of the growing bodies by high velocity mutual collisions. This is the result of a synchronism between the velocities of the colliding bodies that provided a sufficiently low mutual collisional velocity, despite the high velocity of both bodies in the central reference plane of the disk. There are still aspects of this model that need further attention, such as the details of the transition of this phenomenon at the stage that mutual perturbations of the growing planets become comparable to those of the giant planets, however this does not seem likely to be a major difficulty as a consequence of some approximate calculations regarding this transition.

Much of this work has been published (Kortenkamp and Wetherill, 2000; Kortenkamp et al., 2000b; Kortenkamp et al., 2001). The third of these references points out that this same "type 2" runaway is also likely to be significant in young multiple-star systems and the post-supernova environment in binary-pulsar systems. Dr. Kortenkamp is continuing this research at the Planetary Science Institute in Tuscon, AZ with other financial support.

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Kortenkamp, S. J., and G. W. Wetherill, Terrestrial planets and asteroid formation in the presence of giant planets. Relative velocities of planetesimals subject to Jupiter and Saturn perturbations, *Icarus*, 143, 60-73, 2000.

Kortenkamp, S. J., E. Kokubo, and S. J. Weidenschilling, Formation of planetary embryos, in *Origin of the Earth and Moon*, R. M. Canup and K. Righter, Eds., pp. 85-100, University of Arizona Press, Tucson, 2000.

Kortenkamp, S. J., G. W. Wetherill, and S. Inaba, Runaway growth of planetary embryos facilitated by massive bodies in a protoplanetary disk, *Science*, 293, 1127-1129, 2001.

Boss, A. P., and G. W. Wetherill, Rapid formation of ice giant planets, *Icarus*, 156, 291-295, 2002.